Process Integration Project

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Outline

- Project Success Elements
- Process Integration
  - Concept
  - Objectives
  - Terminology
  - Activities
- Future Plans
- Extra Slides for Questions

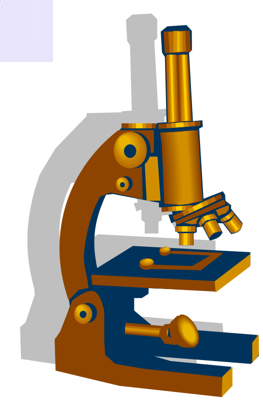
Project Success Elements

Widget
(it's an Mac thing)

Facilities

People

Equipment



The NCPV's Strength…

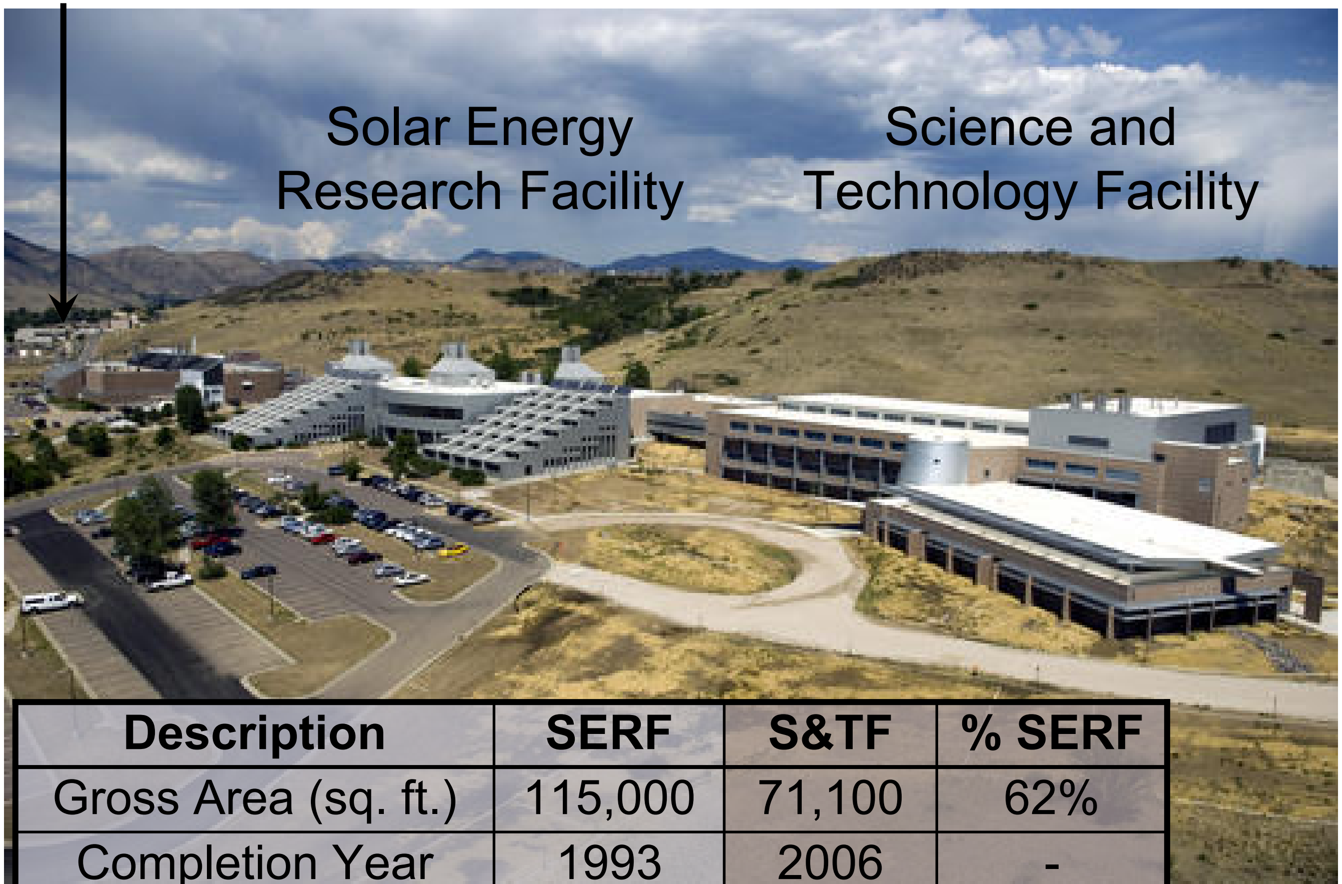
Measurements & Characterization Group	Electronic Materials & Devices Group	Technology Applications & Reliability Group	Direct Reports
Manager **Pete Sheldon**	Manager **John Benner**	Manager **Carol Riordan**	Manager **Larry Kazmerski**
AA Audrey Carapella	AA Carole Allman	AA Paula Robinson	AA
Div. # 5210	Div. # 5220	Div. # 5230	Div. # 5240
5211 **Analytical Microscopy** Mowafak Al-Jassim	5221 **High Efficiency Devices & Concentrators** Sarah Kurtz	5231 **Engineering & Reliability R&D** Carol Riordan	5241 **PV Program Manager** Larry Kazmerski
5212 **Cell & Module Performance** Keith Emery	5222 **Silicon Materials & Devices** Howard Branz	5232 **Technology Development** Martha Symko-Davies	5242 **Emeritus** Larry Kazmerski
5213 **Surface Analysis** Sally Asher	5223 **Polycrystalline Compound** Rommel Noufi	5233 **Technology Acceptance** Cecile Warner	5243 **Research Fellow** Larry Kazmerski
5214 **Electro-Optical Characterization** TBD	5224 **Process Development & Engineering** David Ginley	5234 **PV Engineering, Test & Evaluation** Bill Marion	5244 **Post Doc** Larry Kazmerski
5215 **Process Integration Development** Brent Nelson			

…

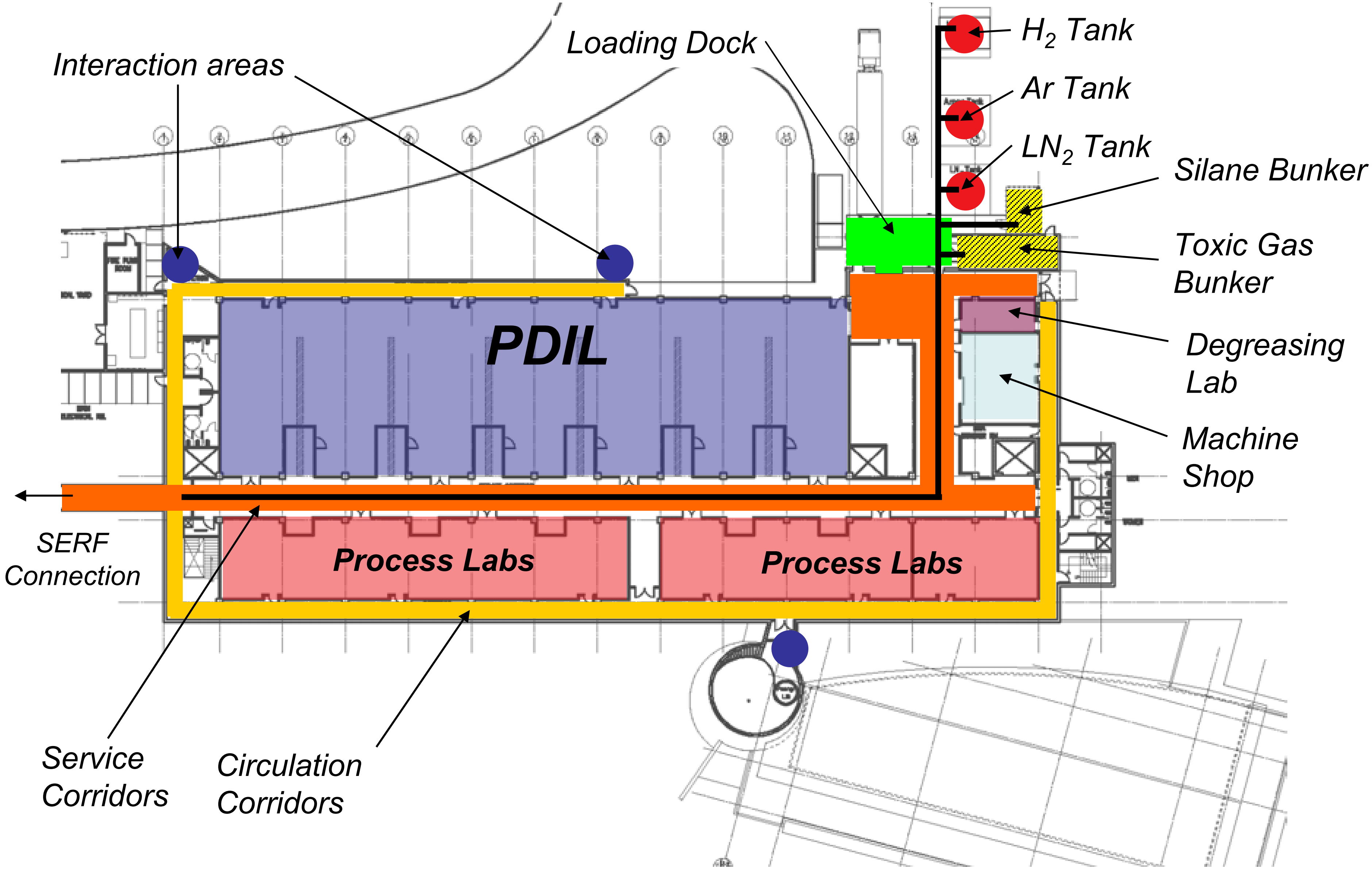
Needed: Integration skill-sets.

The NCPV's Facilities…

Outdoor Test Facility



Description	SERF	S&TF	% SERF
Gross Area (sq. ft.)	115,000	71,100	62%
Completion Year	1993	2006	-
Lab Area (sq. ft.)	29,040	23,608	81%
Offices	~160	~55	34%



The S&TF Second Floor

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Typical Material Science Cycle…

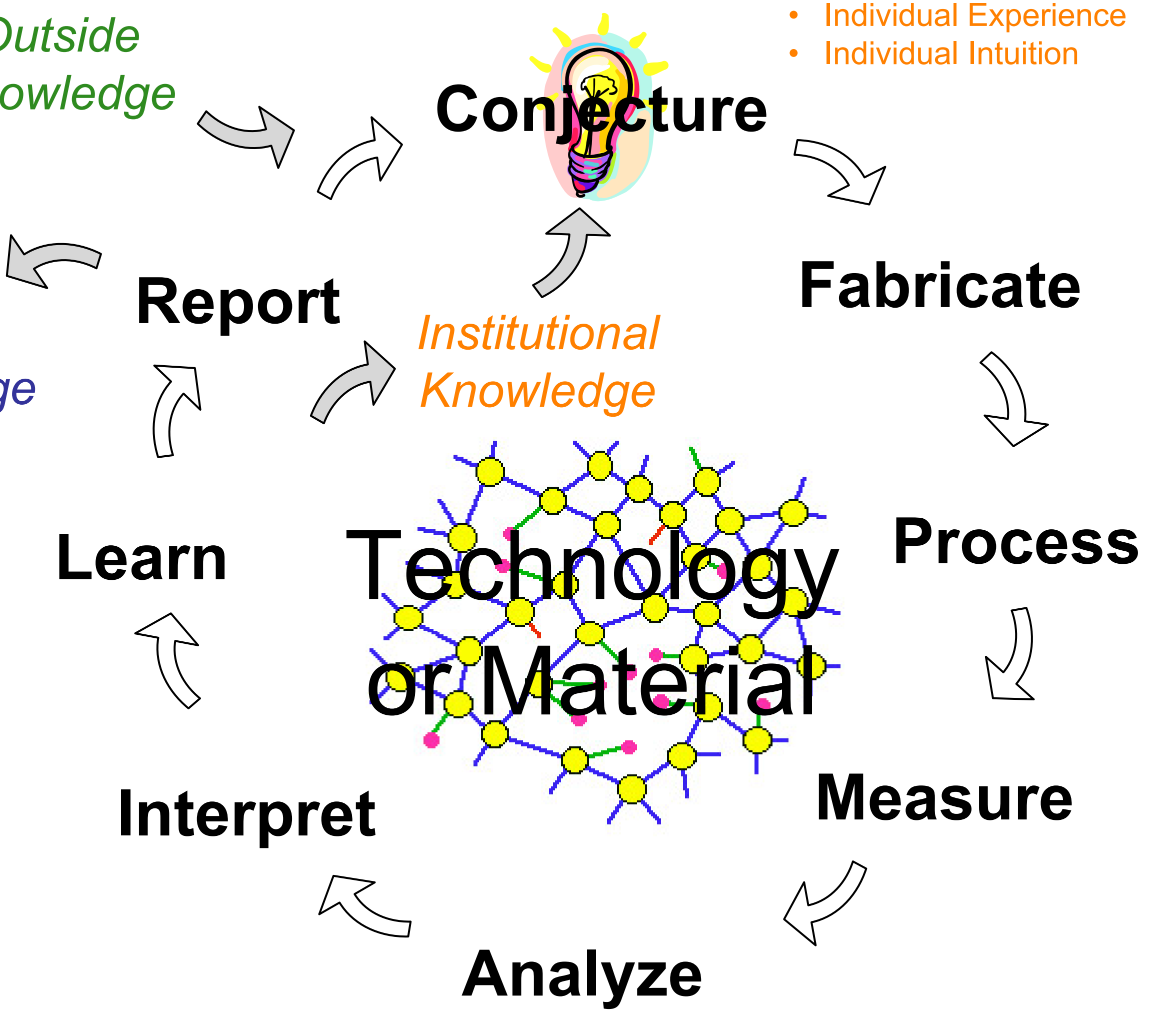
- Attending Conferences
- Reading Publications
- Sabbaticals to NREL
- Seminars
- Technical Interactions

Outside Knowledge

- Laboratory Notebooks
- Internal Reports
- Individual Training
- Individual Experience
- Individual Intuition

- Patents
- Presentations
- Publications
- Sabbaticals Away
- Technology Transfer

Shared Knowledge

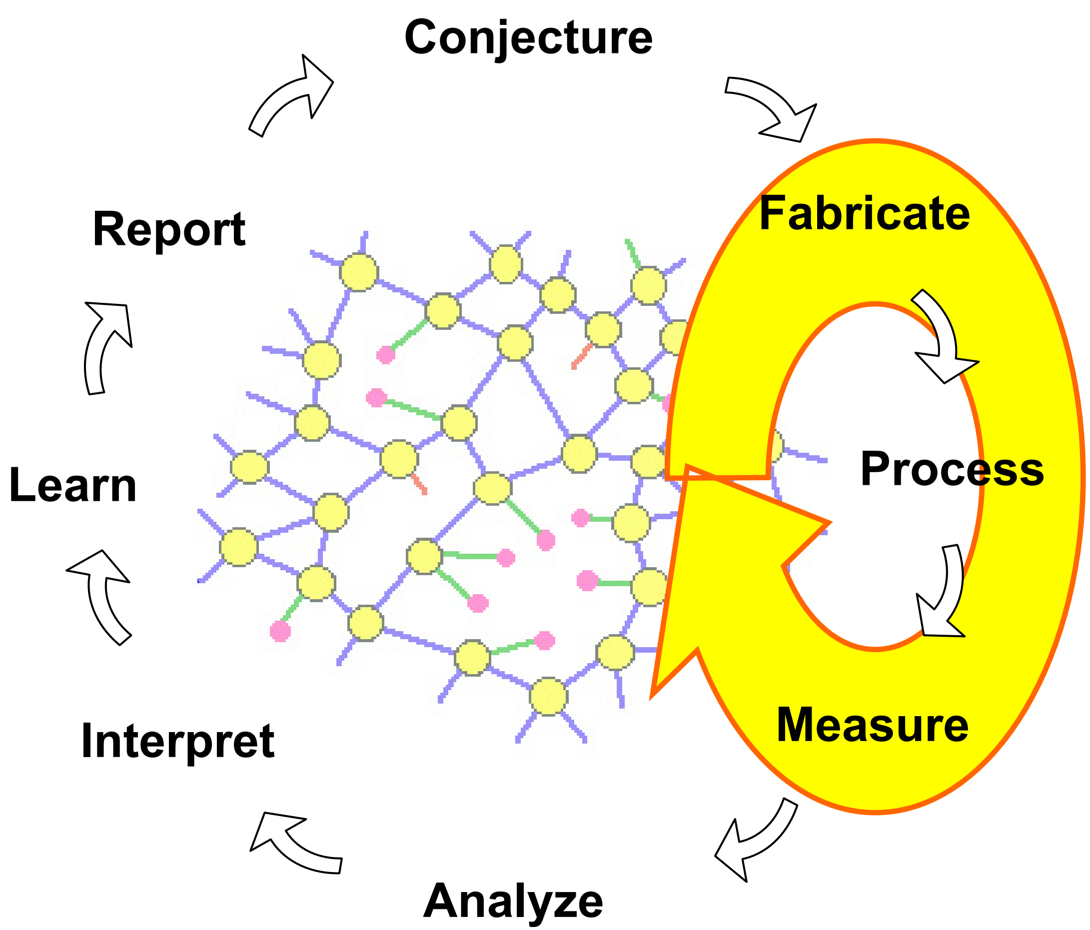


Of course progress is made over time.

What if…

So that

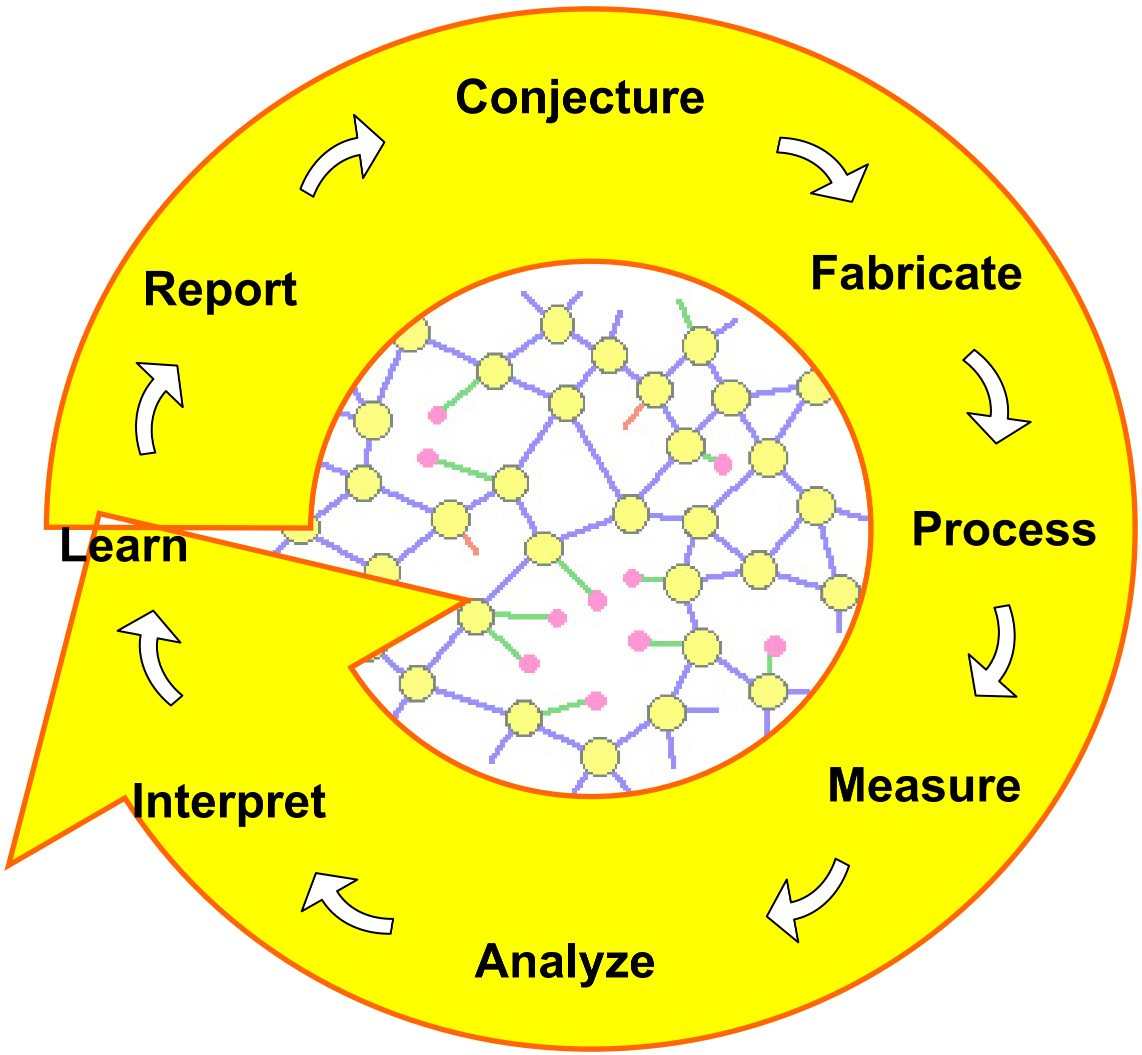
- there are no air breaks between steps
- any amount of steps can be sequenced in any order



… all the tools were integrated?

What if…

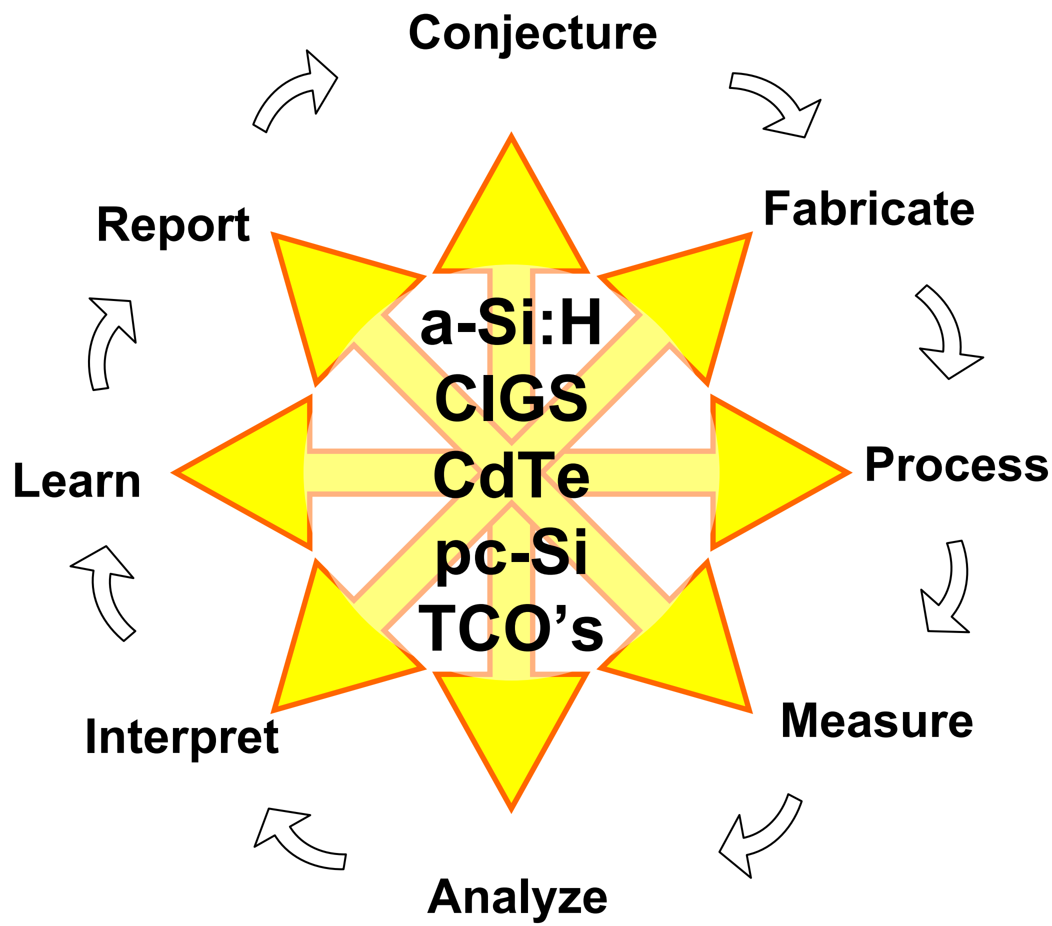
So that
- analysis was facilitated
- control of deposition, processing, and measurement was automated
- the entire history of a sample is available to anyone



… all the data was integrated?

What if…

So that
- device designs are not limited by existing technologies
- experts from various materials and characterization specialties work together to answer specific questions
- combinatorial techniques were incorporated as appropriate



… all materials were integrated?

Process Integration Vision

- Integrate deposition, characterization, and processing tools
  - Flexible and robust
  - Standardized transfer interface
  - Standardized sample size (~ 6” x 6”)
  - Controlled sample ambient between tools
  - Integrated and secure data handling
- Benefits
  - Answers to previously inaccessible research questions
  - Control and characterization of critical surfaces (interfaces) and their impact on subsequent layers
  - Assess process-related source chemistry, surface chemistry and kinetics, and bulk reconstruction
  - Grow layers and alter interfaces using controlled processes and transfer ambients (without exposure to air)
  - Develop new techniques, methodologies, device structures, materials, and tools (growth, processing, and analytical)
  - Integrate virtually any of combination of capabilities built to the standards
  - Improved collaborations with university and industry researchers

Animation

- Process Integration Animation
- Download at:
  ftp://ftp.nrel.gov/pub/bnelson-out/Process_Integration_Files/Movies

Maximum Substrate Size Drives Everything Else

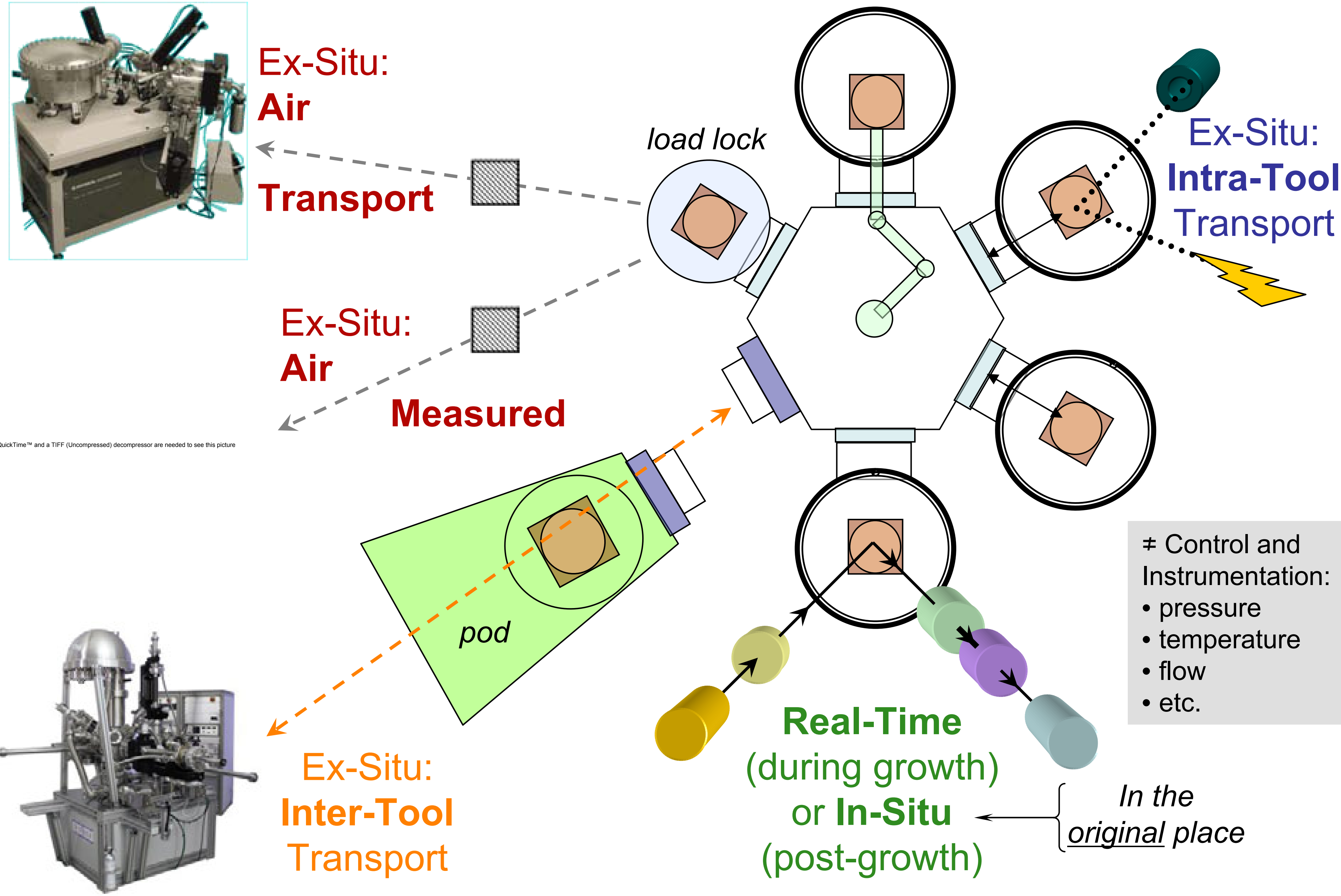
157 x 157 mm Maximum

- 6.18” x 6.18”
- supports the multi-crystalline silicon industry (56% of PV)
- supports other technologies (44%)
  - single crystal silicon (round)
  - thin-films (a-Si, CdTe, CIGS) by using a commercially relevant size
  - third generation PV

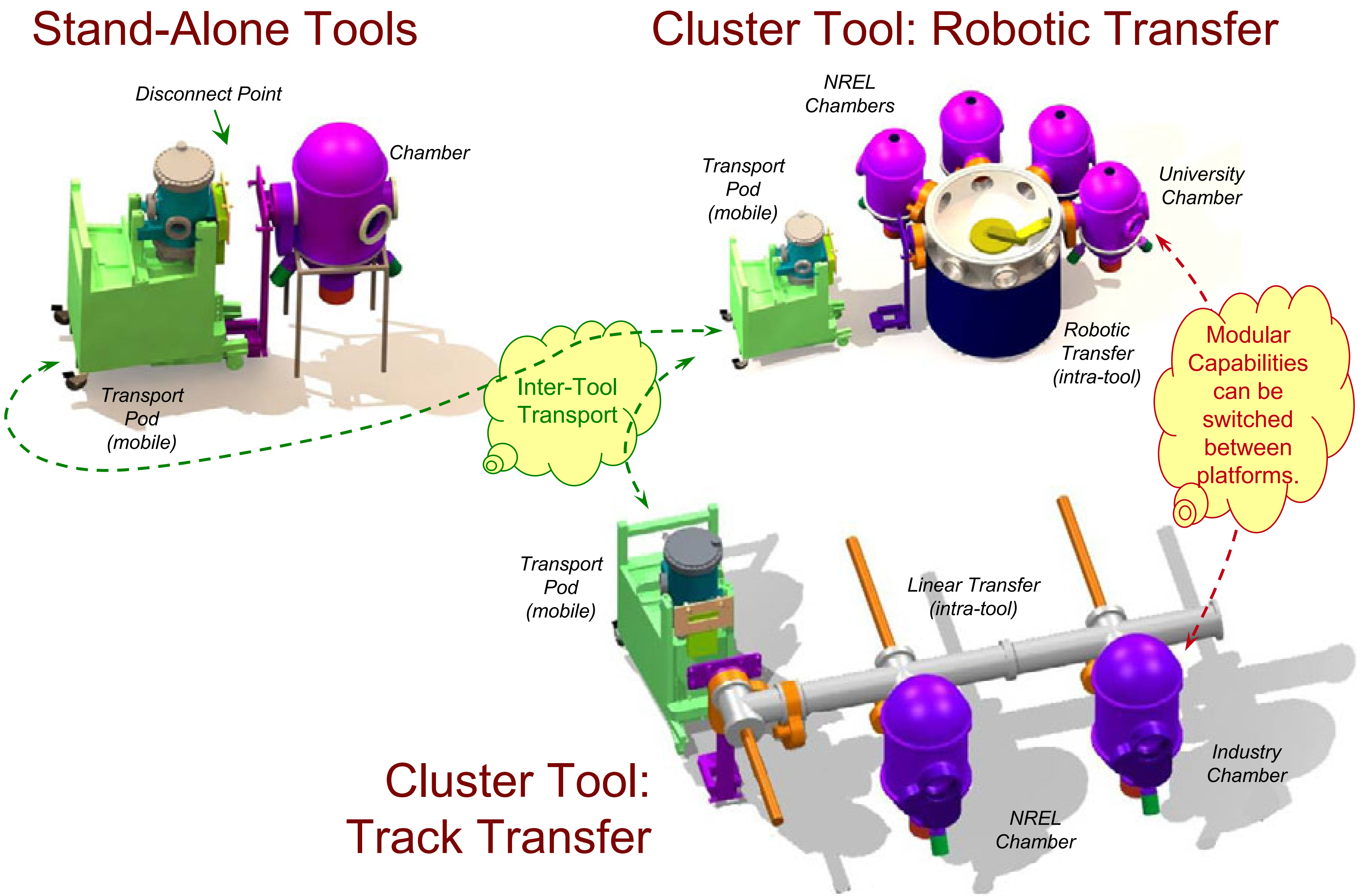
Substrate Materials

- (poly) crystalline wafers
- soda lime glass
- aluminosilicate glass
- stainless steel
- exotic & specialized

Measurement Classifications



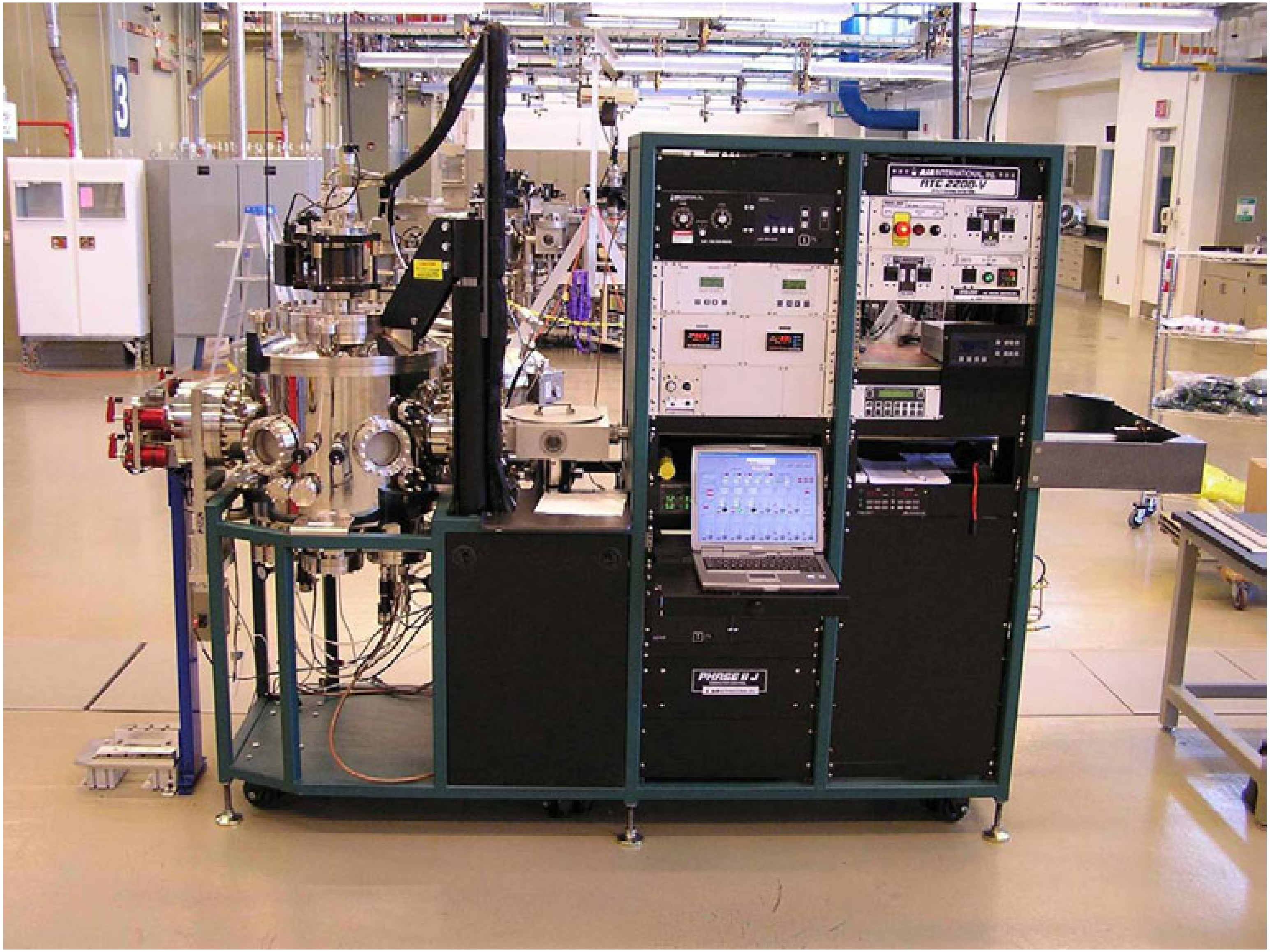
Inter-Tool Transport via Pod



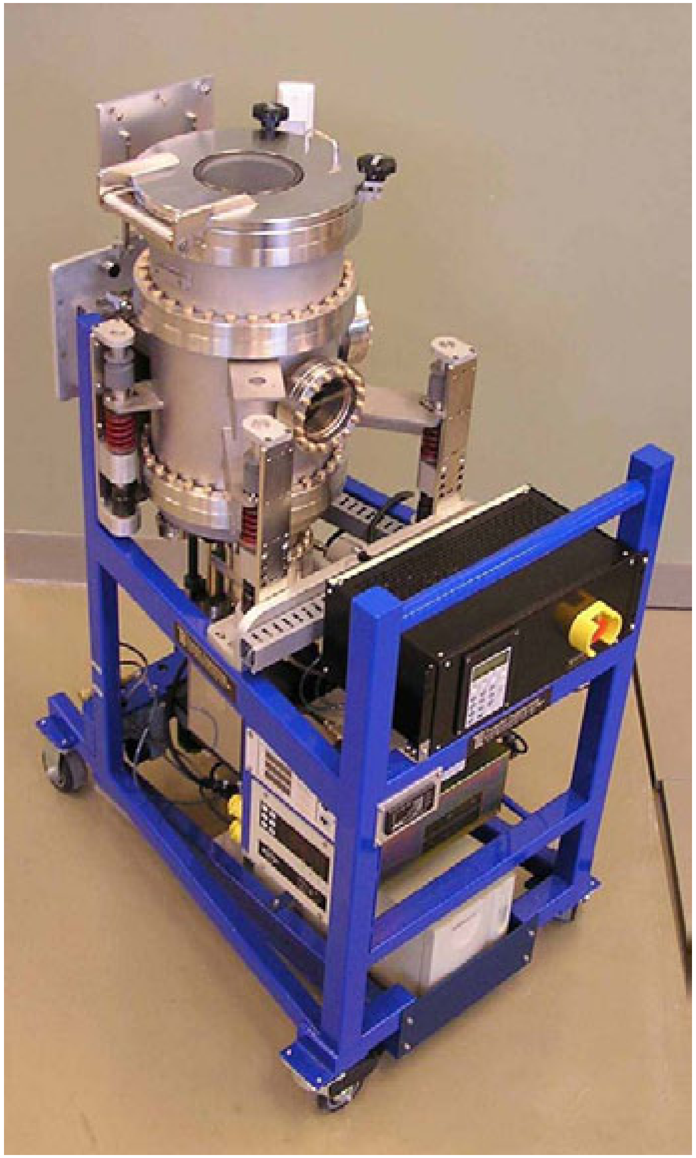
Process Integration Equipment

- Integrated Equipment Delivered
  - TCO Sputtering Tool
  - Mobile Pod
  - Silicon Cluster Tool
- Support Equipment
  - Profilometer
  - Interferometer
  - Ellipsometer
- Integrated Equipment being Developed

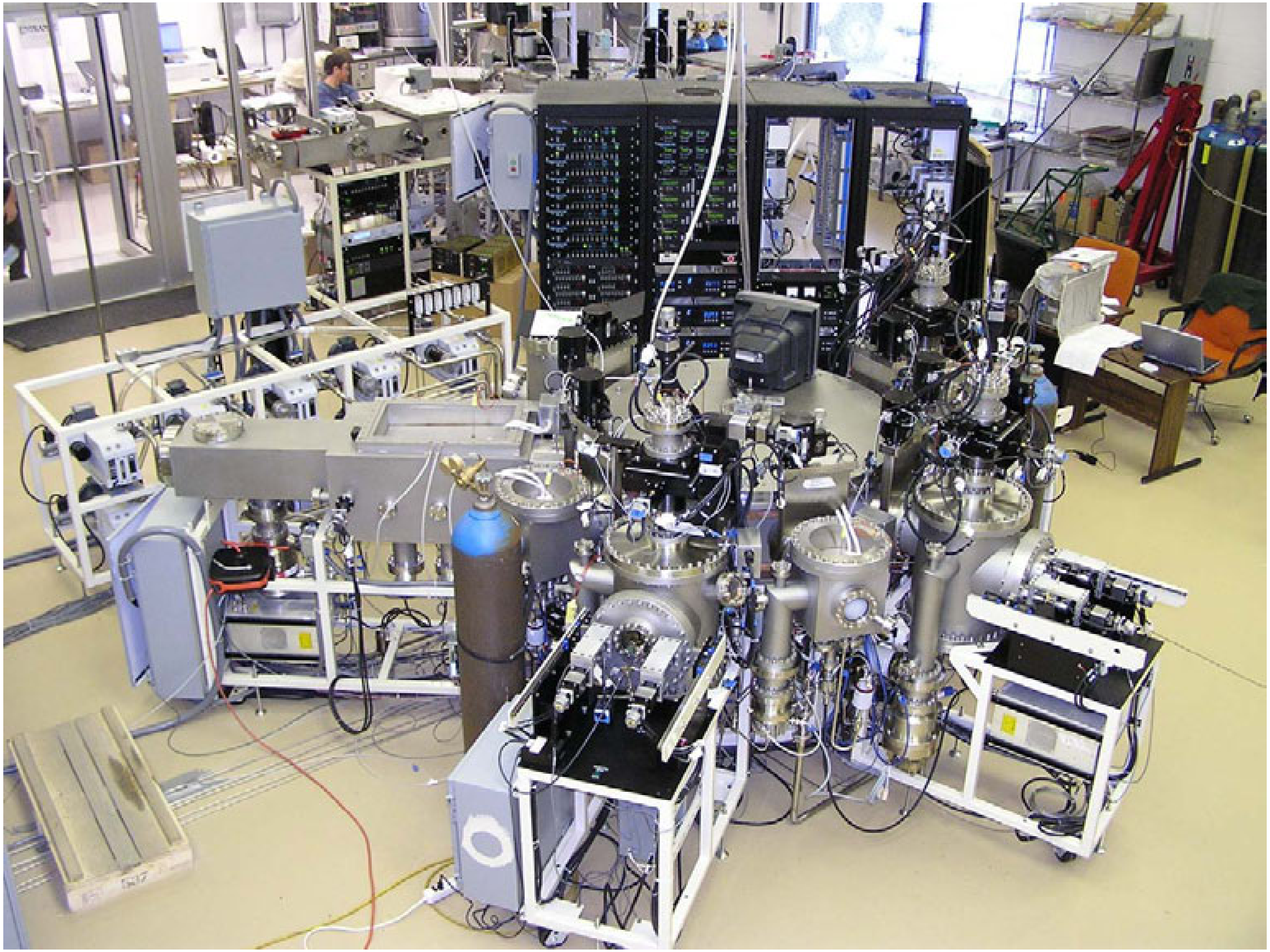
TCO Sputtering Tool



Mobile Pod

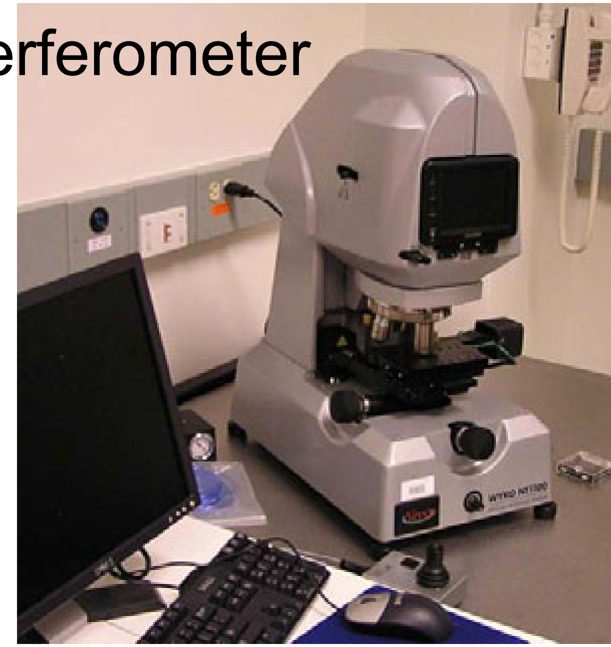


Silicon Cluster Tool

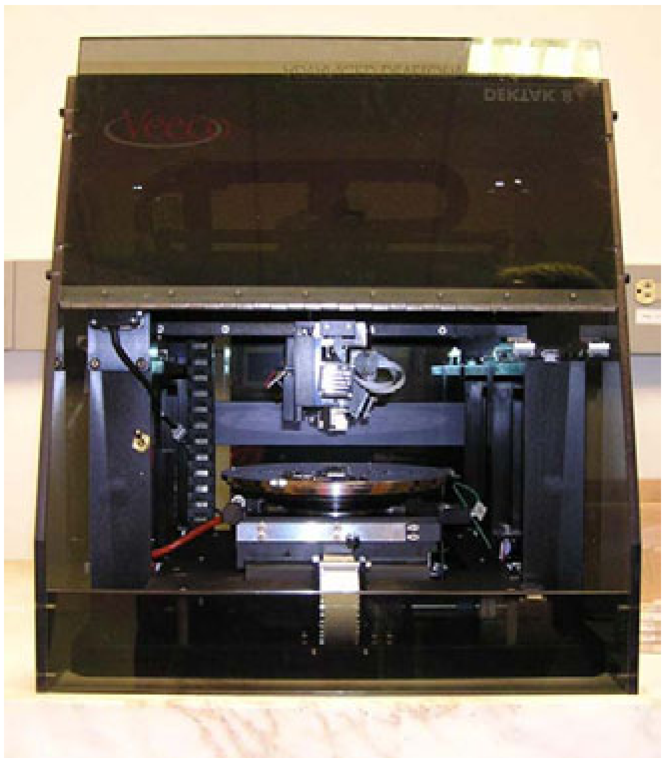


Support Equipment

Interferometer



Profilometer



Ellipsometer

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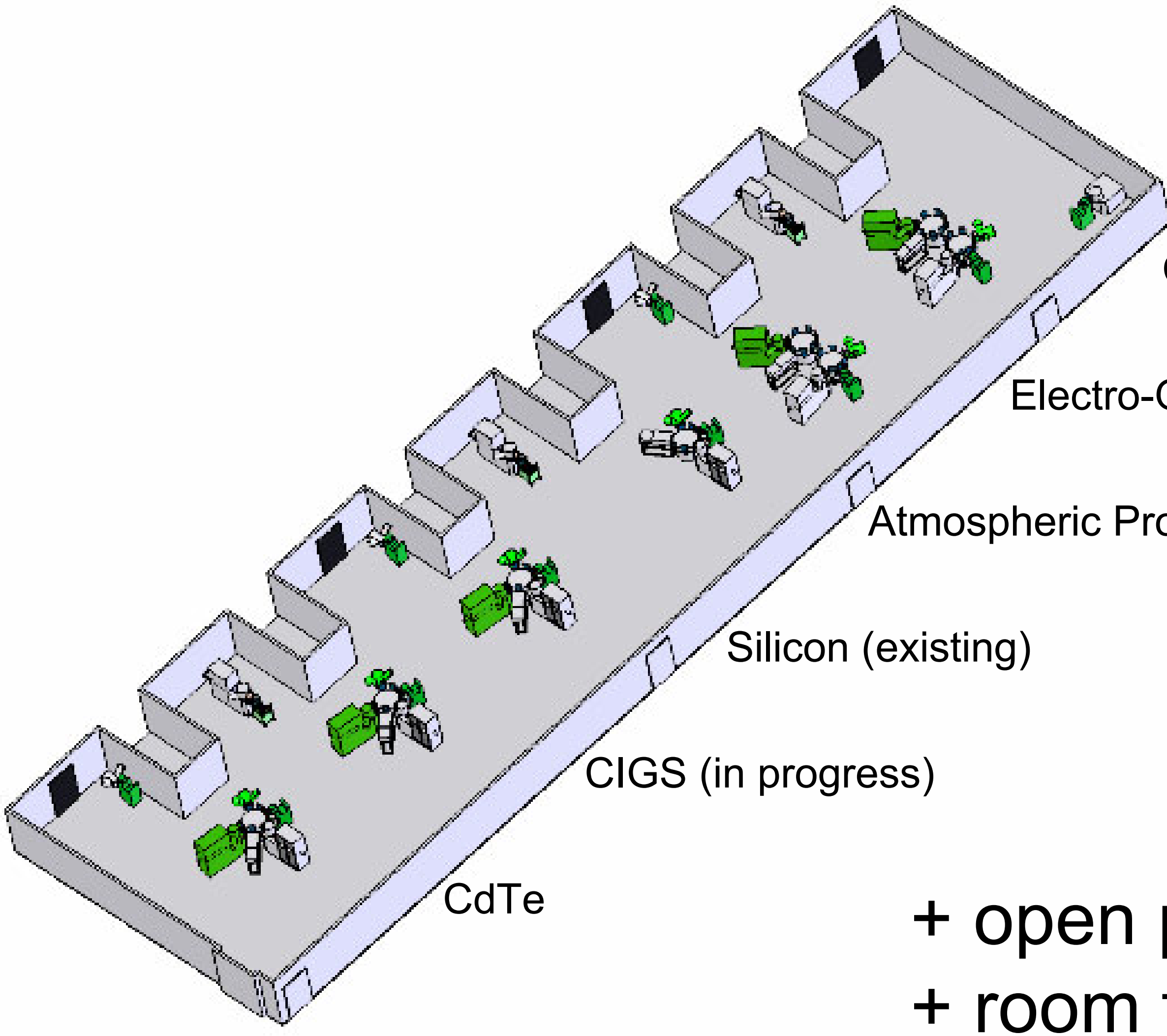
S&TF Essential Capital Equipment

Item	Status	Budget ($k)
Transport Pod & Tooling	Operational	$105
TCO Sputtering Tool	Operational	$336
Silicon Platform	Installing	$1,250
Support Equipment	Mixed	$409
CIGS Platform	Awarded	$1,200
Modular Auger Tool	Awarded	$550
CdS by CBD	Building	$55
XPS and UPS Tool	Developing	$1,250
Electro-Optical Platform	Developing	$1,450

Future Plans



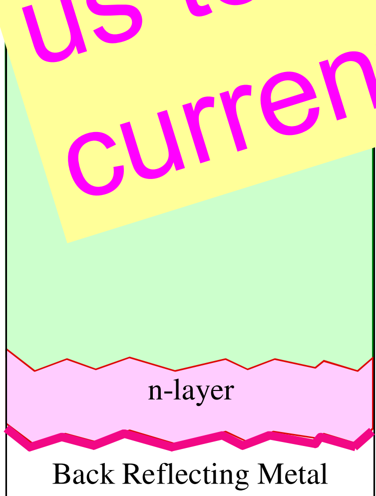
+ open ports on platforms
+ room for more

Bottom Line

<u>We Must Improve Our Understanding</u>

- Materials properties and their
  - effect on device performan
  - influence on oth
- Interfac

We need to build tools that allow us to answer questions we currently cannot satisfy.



<u>We Must Develop New:</u>

- Device Structures
- Deposition Techniques
- Process Monitoring Techniques
- Material Characterization Techniques

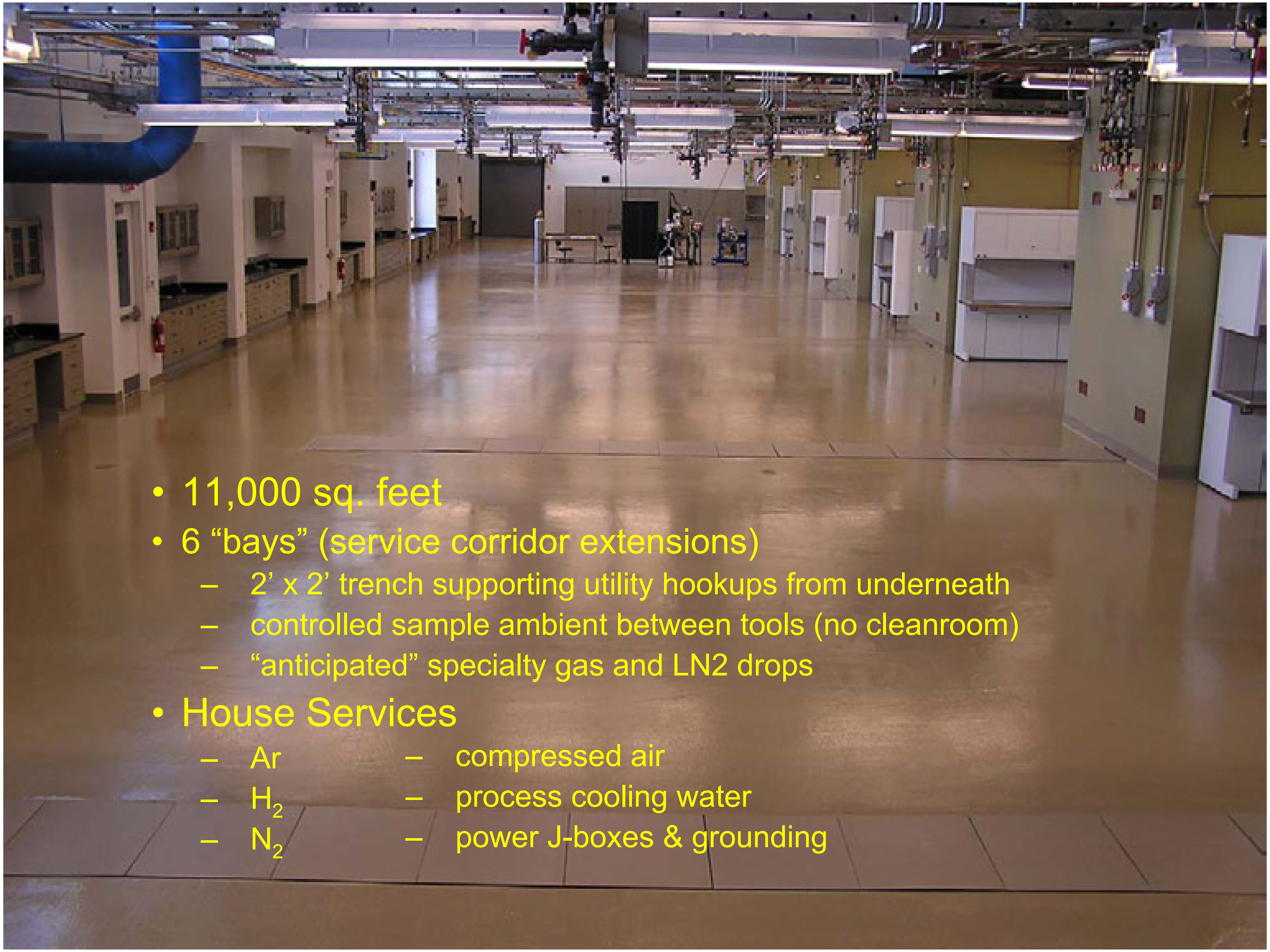
Outline

- Project Success Elements
- Process Integration
- Future Plans
- Extra Slides for Questions
  - PDIL (+ separate file)
  - Process Integration Concept Expansion
  - Process Integration Choice Summaries
  - Is SEMATECH a model for PV (in separate file)
  - Business Case Analysis (in separate file)

PDIL Concept

- A facility that provides
  - flexible access to various utilities
  - large space to bring in big equipment (clusters)
  - minimal physical barriers to tool arrangement
  - space not owned by one internal “silo”
- A facility that makes possible
  - easy inter-tool integration via the mobile pod
  - easy distribution of subject matter experts to multiple tools
  - the process integration concept

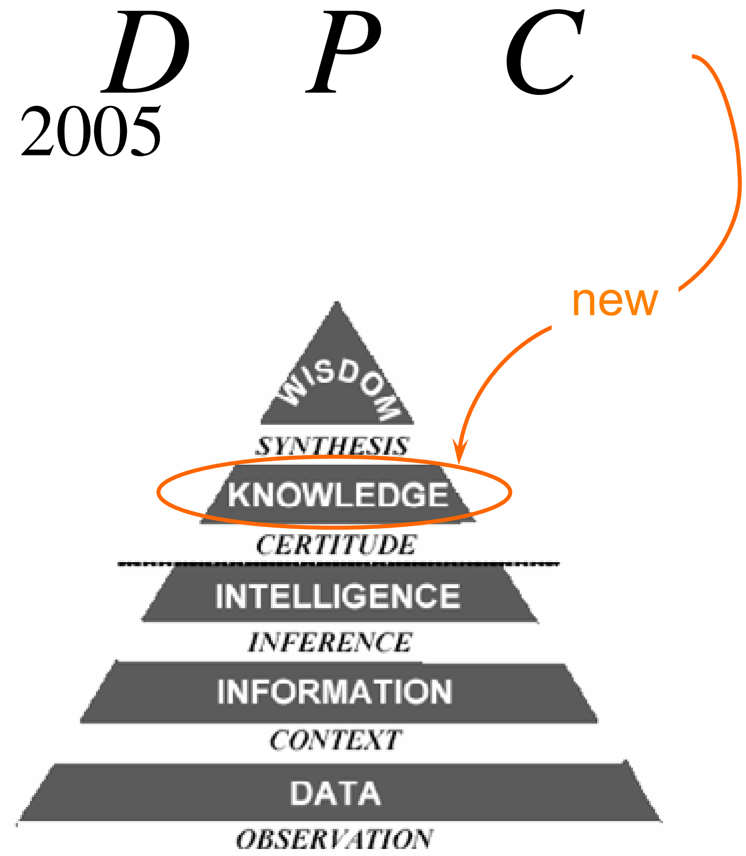
Process Development Integration Lab



- 11,000 sq. feet
- 6 “bays” (service corridor extensions)
  - 2’ x 2’ trench supporting utility hookups from underneath
  - controlled sample ambient between tools (no cleanroom)
  - “anticipated” specialty gas and LN2 drops
- House Services
  - Ar
  - H_2
  - N_2
  - compressed air
  - process cooling water
  - power J-boxes & grounding

Process Integration: So What

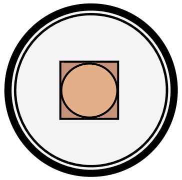
- Build Equipment
  - Deposition (D)
  - Processing (P)
  - Characterization (C)
- With the right operators
- Build the knowledge base



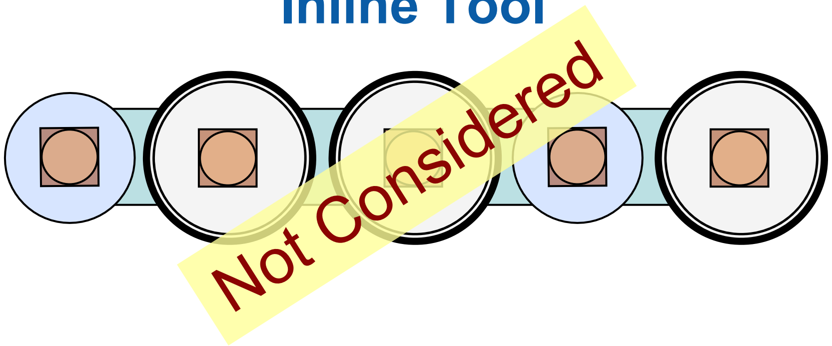
Haeckel's Hierarchy, Barabba and Zaltman, Harv. Bus. Sch. Press, 1991

Chamber Integration Options

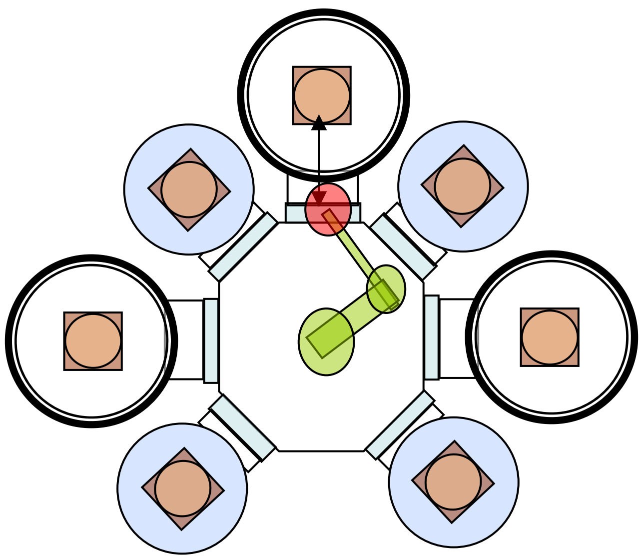
Stand-Alone Tool



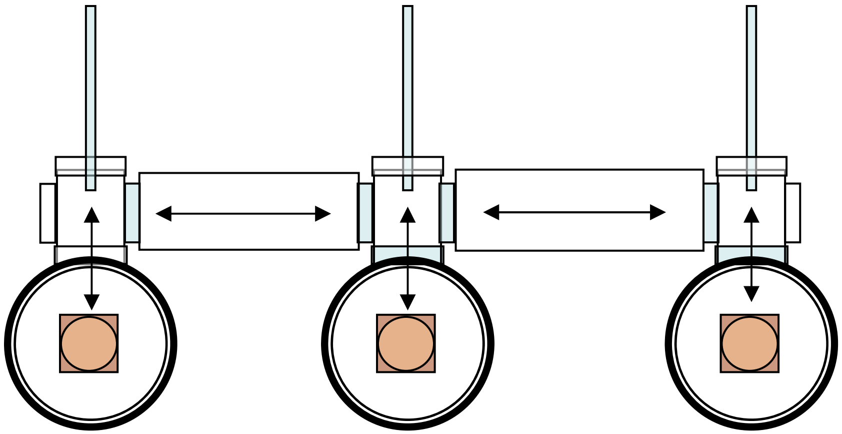
Inline Tool



Cluster Tool: Robotic Transfer



Cluster Tool: Tracked Transfer



Path to Integrated Tools

- Establish design standards for all tools consisting of:
  - maximum substrate size and shape
  - platen to hold substrates of various size and shapes
  - transfer mechanism for platens within tools (intra-tool)
  - transport of platens between tools via a mobile pod (inter-tool)
  - pod to tool interface (dock)
- Design and procure the first tool(s) using these standards
- Prioritize techniques necessary for future research
- Choose integration type (platforms) for each technique
- Design and procure actual tools
  - prioritize real-time and in-situ characterization
  - maximize modularity of individual tools (chambers, techniques)
- Optimize tool function
- Facilitate collaborations with Universities and Industry

Threats & Constraints

We Must Receive Capital Equipment Requests:

- Typical Semiconductor manufacturing tool ≈ $4M
- Typical Semiconductor tool installation cost ≈ 20%
- Easily fit 12 Semiconductor tools into PDIL

Core Groups Must Allocate Human Resources:

- The group must define the functionality of their tool(s)
- Assign someone work with the process integration and engineering/facilities staff as-well-as the vendor(s)
- Support from EM&D Engineering Group as needed

Hire Full-Time Software Specialists Soon:

- Upfront software integration costs ≈ 40% of development
- The software integration of tools after development and construction ≈ 4 X the initial cost

Issues to Resolve

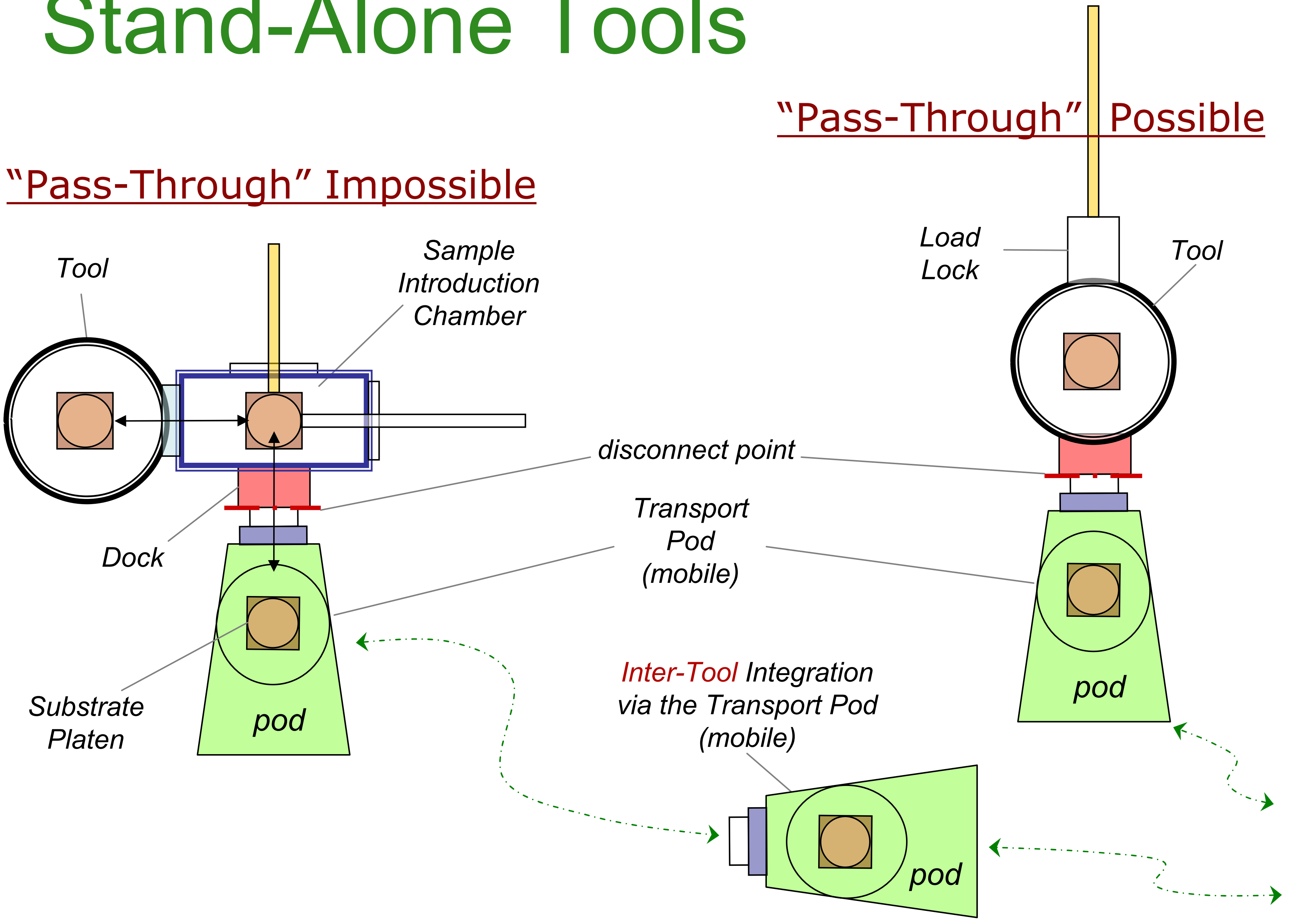
- Software
  - control
  - data management
  - David Albin, Jeff Alleman, Russell Bauer, Pat Dippo, Daniel Friedman, Tom Moriarty, Brent Nelson, Steve Robbins, Pete Sheldon, Pauls Stradins, Yanfa Yan
- Co-Locating "Right" Tools
- Expansion
- Combinatorial
- Masks
- Secondary (smaller) Standard
- External Advisory Committee
- Move from ex-situ → in-situ → real-time
  (please stick around for nomenclature discussion)
- Overcome "tax" mentality → collective capacity

Tool Integration Options

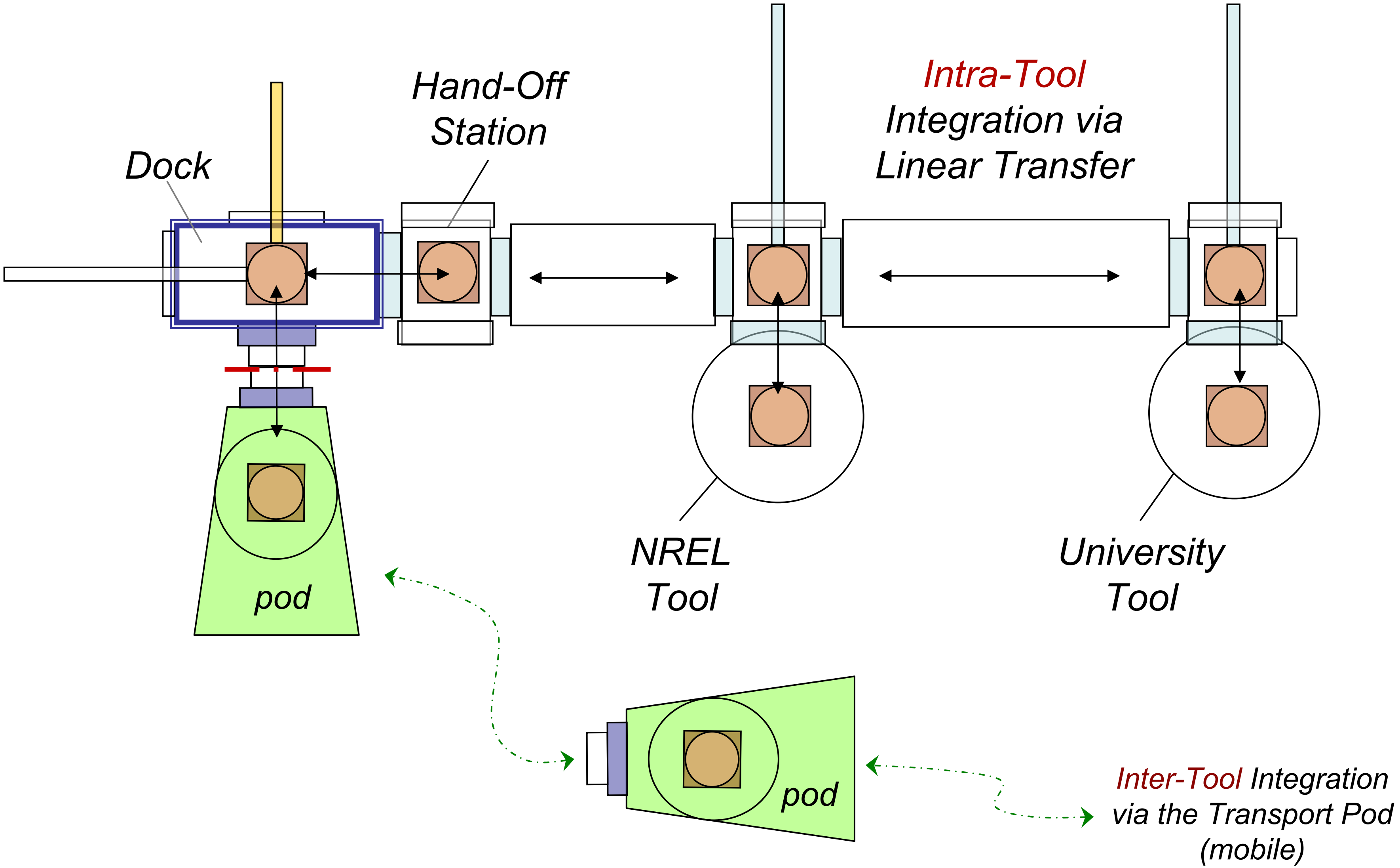
Consideration	Stand-Alone (single-tool)	In-Line (multi-tool)	Robotic Cluster	Tracked Cluster
Use a standard platen	+	+	+	+
Dock a standard pod	+	+	+	+
Eliminate full air exposure between steps	•••	•••	•••	+
Short transfer time	—	+	+	—
Robust	+	+	+	—
Flexible	+	—	+	+
Sequence process steps in any order	+	—	+	+
Combine materials not normally combined	+	—	+	+
Bottom Line (Application)	**Specialized Techniques**	**Not Considered**	**Ideal for Deposition**	**Some Analytical**

Not Considered

Stand-Alone Tools



Cluster Tools: Track Transfer



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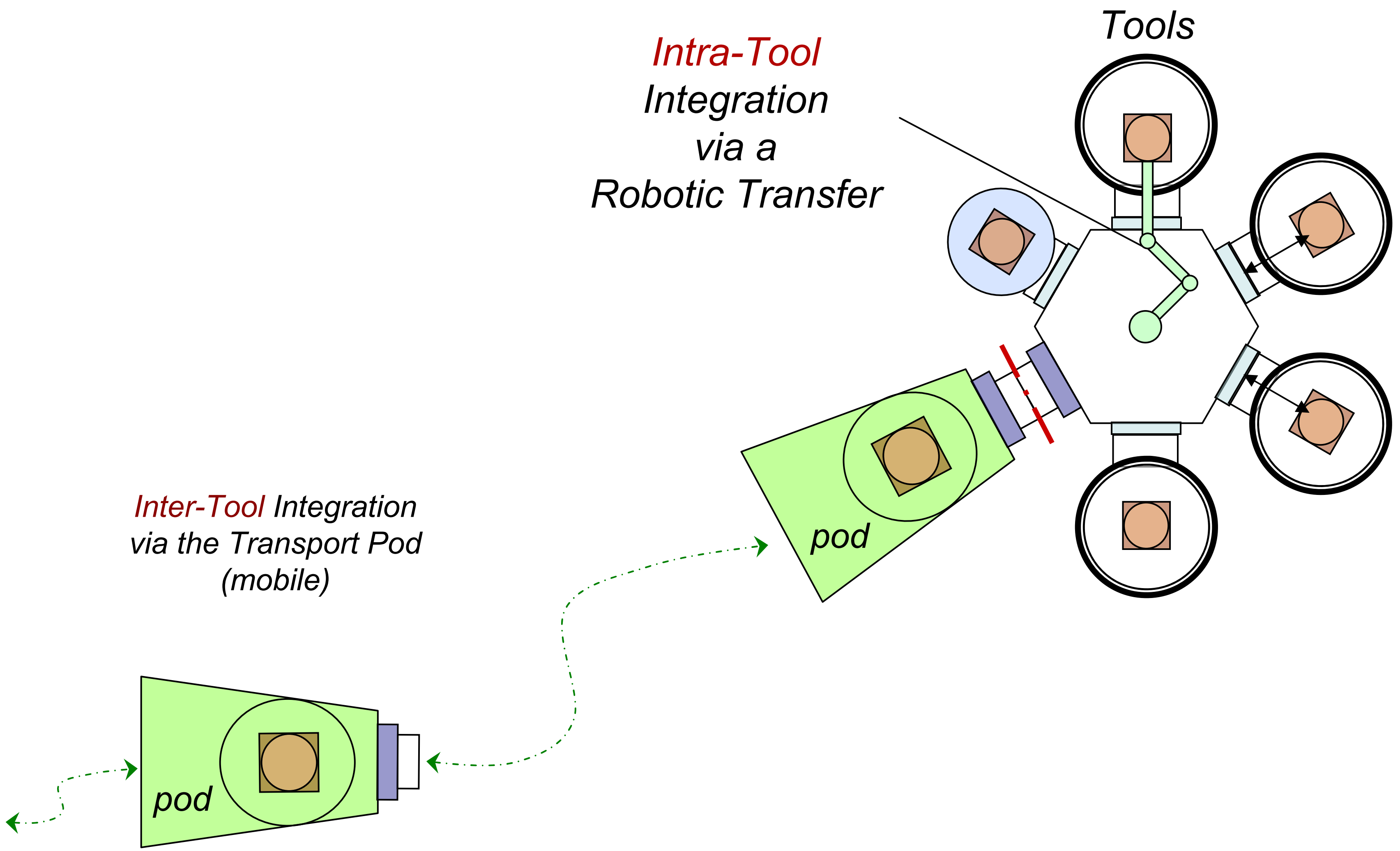
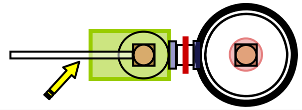
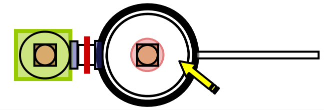
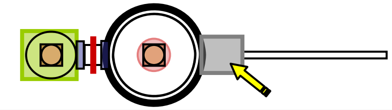


Stand-Alone Platform Comparison

Consideration	Manual Transfer[1]	Robotic Transfer[2]
Transfer Automation	– Difficult to fully automate	+ Designed for full automation
Throughput[3]	– Low: Limited automation	+ High: Full automation
Robustness	– Multiple manual alignments	+ Robots designed for 24/7 use
Footprint[4] (no extra tools, same functions)	– alpha design: 8'-2" x 7'-3"	+ EMS: 3'-4" x 2'-5" + MVS: 6'-1" x 4'-8"
Expandability (min. = pod + tool)	– Can only add cassette & flipping	+ e.g., 4-port can add 2 functions + e.g., 8-port can add 6 functions
Dock Vacuum Level	+ 10^{-8} Torr spec.ed (may be tricky) – Transfer time in minutes	– 10^{-6} Torr guaranteed, 10^{-8} possible + Transfer time in seconds
Cost for Dock (no pod or tools)	+ 70 - 85 % of a robot	+ once a second tool is added, per tool cost is less than manual

1 An X-Y transfer where platens are loaded from the pod in X and translated to a working chamber in Y.
2 The dock consists of a chamber containing a robot arm rather than linear, external manipulators in X & Y.
3 Throughput is a separate issue than automation if the time between processing steps needs to be short.
4 A small foot-print means a less lab space is used, but often makes maintenance more difficult.

Standalone Tools: Motion Location

	Consideration	Arm on Transport Pod	Arm on Tool, Effector in Tool	Arm on Load Lock on Tool
Tool	Ports Used on Tool	1) intro and motion	1) platen intro 2) platen motion	1) platen intro 2) platen motion
Tool	Tool Foot Print	no addition on tool	arm: add ~ 48”	arm + LL: add ~ 60”
Tool	X-axis to Sweet Spot	loose 50% access	loose 100% access	loose 100% access
Tool	Tool Complexity	not a through transfer	extra motion to clear[1]	extra motion to clear[1]
Tool	Tool Versatility	must have pod to use	must have pod to use	dedicated LL
Pod	Pod Cleanliness	pod might be LL[2]	pod might be LL[2]	pod is not vented
Pod	Pod Foot Print	arm: add ~ 48”	no addition on pod	no addition on pod
Pod	Pod Mobility	very long pod	small pod	small pod
Pod	Cassette Spacing	larger (or move)[3]	minimal[3]	minimal[3]
Arm	Arm Robustness	mobile (bump hazard)	fixed (safer)	fixed (longest throw)
Arm	Misc. Arm Issues	pod might be LL[2]	exposed to process	routine venting[2]

1 Extra motion may be needed to clear stages out of the arm path when passing through the chamber. If extra motion is not needed, the box could be yellow (it still passes the arm through the process region).

2 The pod doesn’t have to serve as the load lock if platens are loaded from another tool or central load lock. In this case, the box could be green. This is also true to avoid routine venting of the load lock.

3 If the arm is on the pod, the platen spacing needs to allow the arm to pass through or the cassette has to be dropped below the arm for every transfer.

Cluster Tool Platform Comparison

Consideration	Track Transfer[1]	Robotic Transfer[2]
Transfer Automation	– Difficult to fully automate	+ Designed for full automation
Throughput[3]	– Low: Limited automation	+ High: Full automation
Robustness	– Many manual allignments	+ Robots designed for 24/7 use
Footprint	– Larger: Uses up lab space	+ Smaller: Conserves lab space
Expandability	• Add modular sections to the “end of the line”, one-at-a-time	• Robot-to-robot handoff, multiple expansion once “full”[4]
Space Available for Instrumentation	+ Large: Long distances to chambers, long travel possible	– Small: Chambers “clustered” around central robot
Maintenance Access	+ Easy: Lots of space available	– Difficult: Everything packed in
Transfer Zone(s) Vacuum Background	+ 10^{-10} Torr possible – Transfer time in minutes	– 10^{-8} Torr possible + Transfer time in seconds

1 A linear transfer along a “spine” where tools are accessed perpendicularly via a secondary mechanism.
2 Process chambers around a centralized chamber--with a circular form factor--containing a robot arm.
3 Throughput is a separate issue than automation if the time between processing steps needs to be short.
4 Once all ports are full, a new robotic chamber needs connecting via one ports, losing a chamber to hand-off on the existing robot, but adding n-1 ports, where n=ports on new robot. This might be cheaper than adding a n-1 sections to the linear track plus the orthogonal motion to transfer to n-1 chambers.

Clustering of Integrated Tools

Consideration	One-Chamber-at-a-Time[1]	Up Front, All at Once[2]
Cost: Share common elements[3]	Each chamber must stand alone	Sharing possible
Cost: Software integration[4]	X-ch. effort, assembled in end	Taken care of all at once
Cost: Labor	NREL staff, high overhead, not necessarily the right skills	Vendor staff, lower overhead, integration experts & experience
Risk: Working transport	NREL accepts risk by doing it[5]	Vendor provides working tool
Risk: Working software	NREL accepts risk by doing it	Vendor provides working tool
Risk: Funding	Years of funding commitment	Large funding up front
Time: Lost science time	Back end = very large	Up front (planning) = large
Time: Purchasing hoops	X-ch. purchases	One large purchase
Time: To fully integrated tool	X-loops + integration = huge	Functional delivery = baseline[6]
Optimization: Philosophy	Build A, Optimize A, Build B…	Parallel optimization
Optimization: Methodology	Must be materials before devices	Materials in and with devices
Politics: Demonstrates	Uncertainty, poor show-and-tell	Confidence, good show-and-tell

1 Build a chamber, get it working, build the next one, get it working, etc.--integrate them in the end.
2 Fully design and spec. all processes and transport up front and have it delivered as an integrated cluster tool.
3 PLC's, gas lines, software, power distribution, etc. Although, modularity is an advantage, but not universally necessary.
4 SEMATECH: software integration upfront = 0.33 X Tool Development Cost (TDC), after the fact = 4 to 10 X TDC.
5 The biggest risk is that in "off integration optimization" the integration components will be compromised.
6 Process (or measurement) optimization has to be done in both parallel and sequential efforts, no NREL integration work.

Integration Modes

Measurement Class	Transport Ambient	Measurement Location	Measurement Ambient	Measurement Timing
Real-Time	X[1]	process ch.	controlled	during process
In-Situ	X[1]	process ch.	controlled	post or interrupted
Intra-Tool[2]	controlled	same tool	controlled	post deposition
Inter-Tool[3]	controlled	different tool	controlled	post deposition
Mobile Technique[4]	controlled	mobile	controlled	varies w/ technique
Ex-Situ, air transport	air	different tool	controlled	post deposition
Ex-Situ, air measured	air	different tool	air	post deposition

[1] In-Situ: Latin, "in the original place." Real-time diagnostics are a sub-set of in-situ. Once a sample is moved from the original place (chamber), it is an ex-situ measurement, even if it is within the same tool.

[2] Intra-tool transport is the movement of samples between techniques within the same set of interconnected chambers (i.e., the sample transfer within a cluster tool).

[3] Inter-tool transport is the movement of samples between chambers where there is not a direct connection (i.e., independent cluster or stand-alone tools).
The transport pod introduces a new inter-tool capability while maintaining a controlled transport ambient.

[4] A mobile technique is within a chamber that can be moved between tools for a fixed set of experiments.

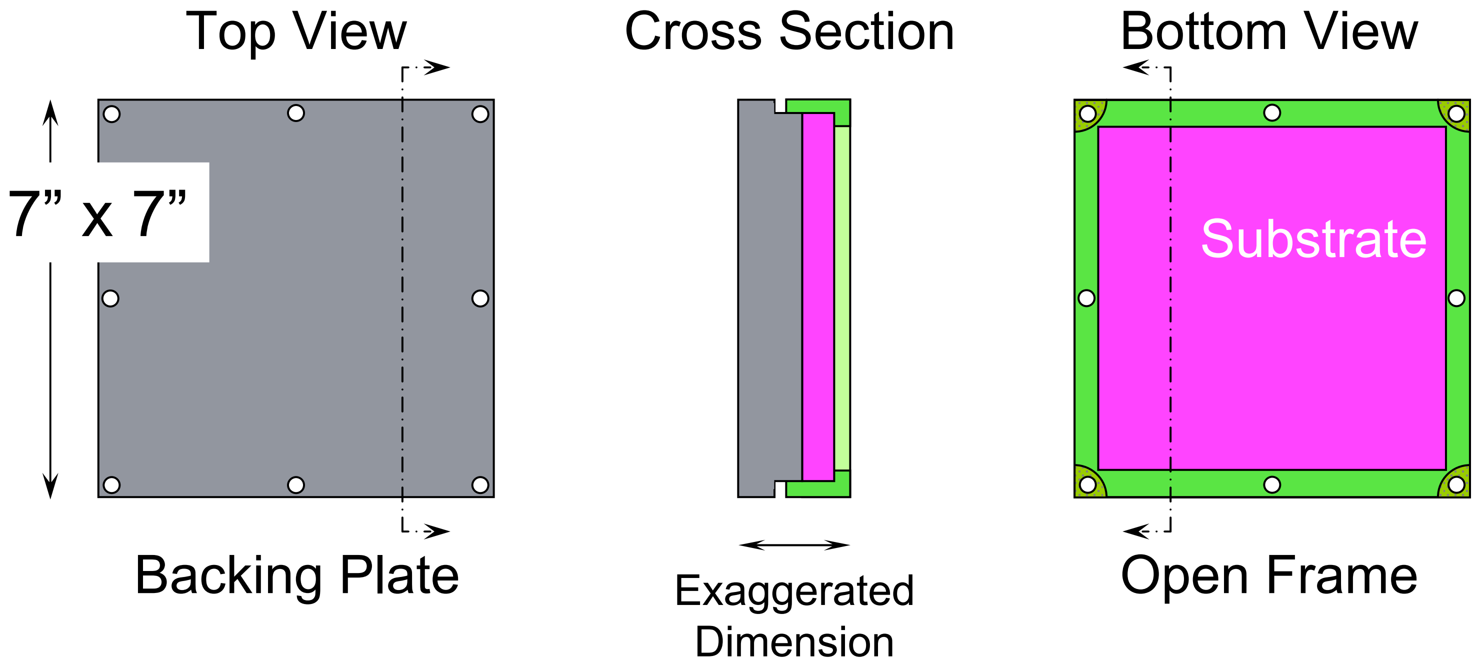
Silicon Support by M&CD

- Electro-Optical Group
  - lifetime measurements (passivation, etc.)
  - IR for oxygen related precipitates
  - ellipsometry (HIT cells, etc.)
- Analytical Microscopy
  - EBIC
  - Cathodoluminescence
  - EBSD
- Surface Analysis
  - SIMS
- Technique Development
  - Reflectivity
- Modeling
  - materials
  - devices
- Conversion and Quantum Efficiency
  - Cells
  - Modules

Intellectual Property

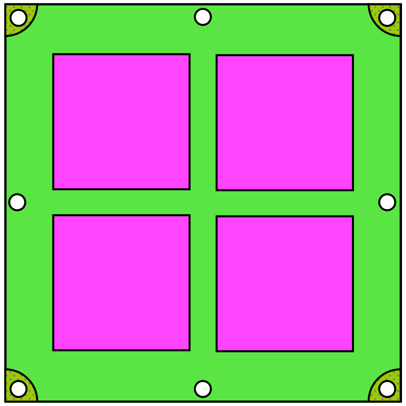
- Protecting IP is a Core Value
  - Computer / data security
  - Sight barriers
  - Case by case contracts
- Mind Set
  - Easy solutions for engineers can be difficult to lawyers
  - Early SEMATECH model *(early days worried more about making progress than protecting IP, shared kitchen design, appliances, and ingredients, didn't share recipes)*
  - Competition *(is nuclear and coal not each other, we need fight the way to the almost infinite trough shoulder to shoulder, not fighting each other before we get there)*
  - Technology Overlap *(reality is PV uses different materials in different form factors using different processes, this is a weakness for standardization, but a strength in protecting IP)*
  - Paranoia *(can you really looking to a "black box" and know what somebody else is doing in there)*

Substrates go in a Platen

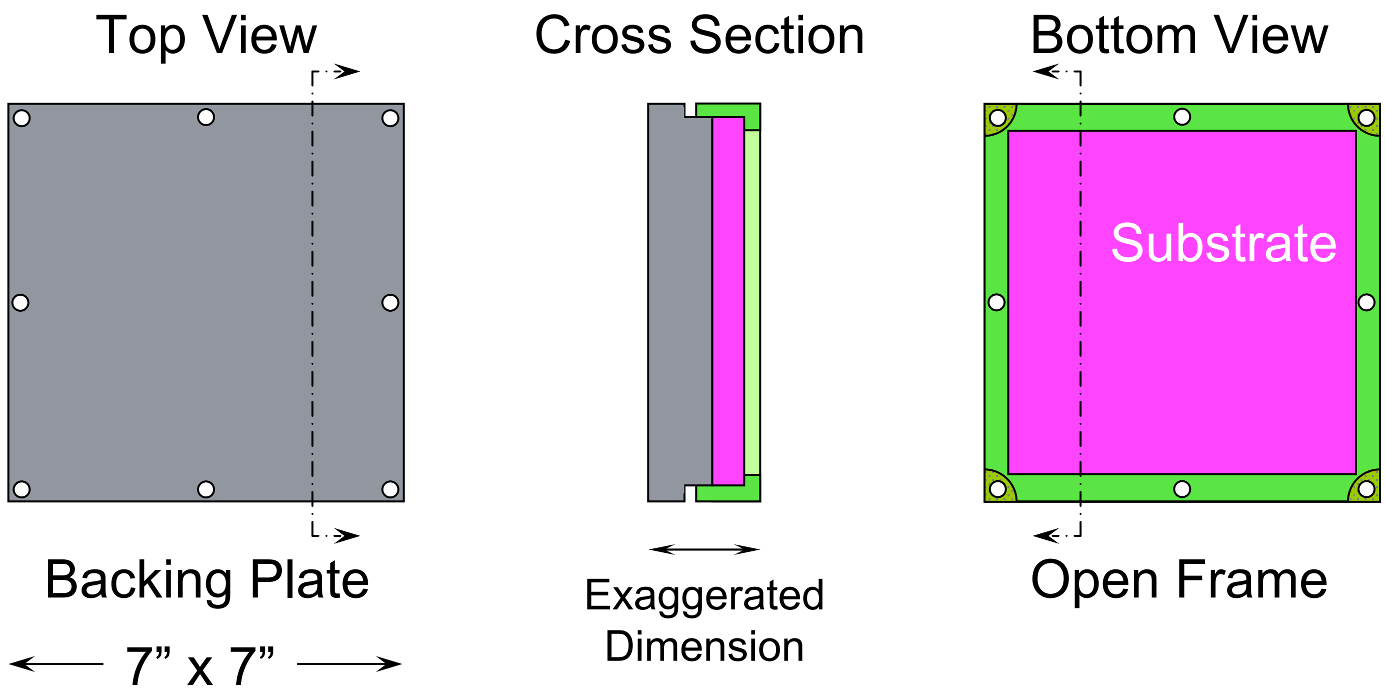


All Systems (that can) will accept this standard 7” x 7” platen <u>form factor</u>.

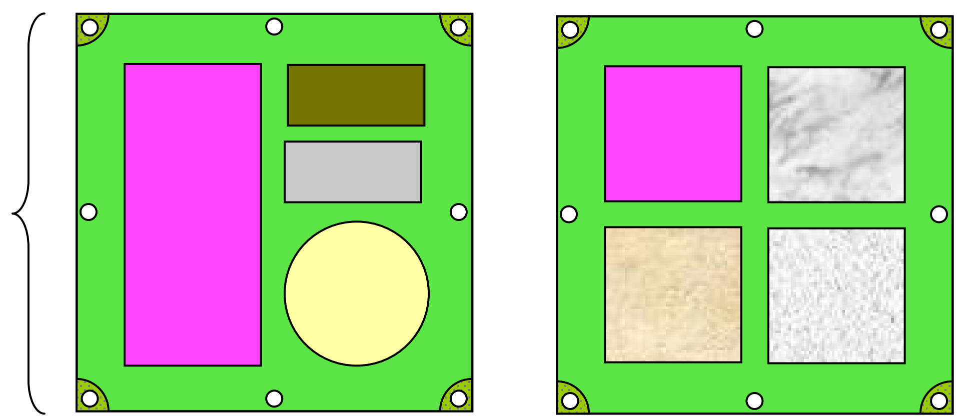
- platens made from Inconel or Molybdenum
- different platen configurations accept various substrate shapes and sizes
  - rounds
  - squares
  - multiple smaller substrates



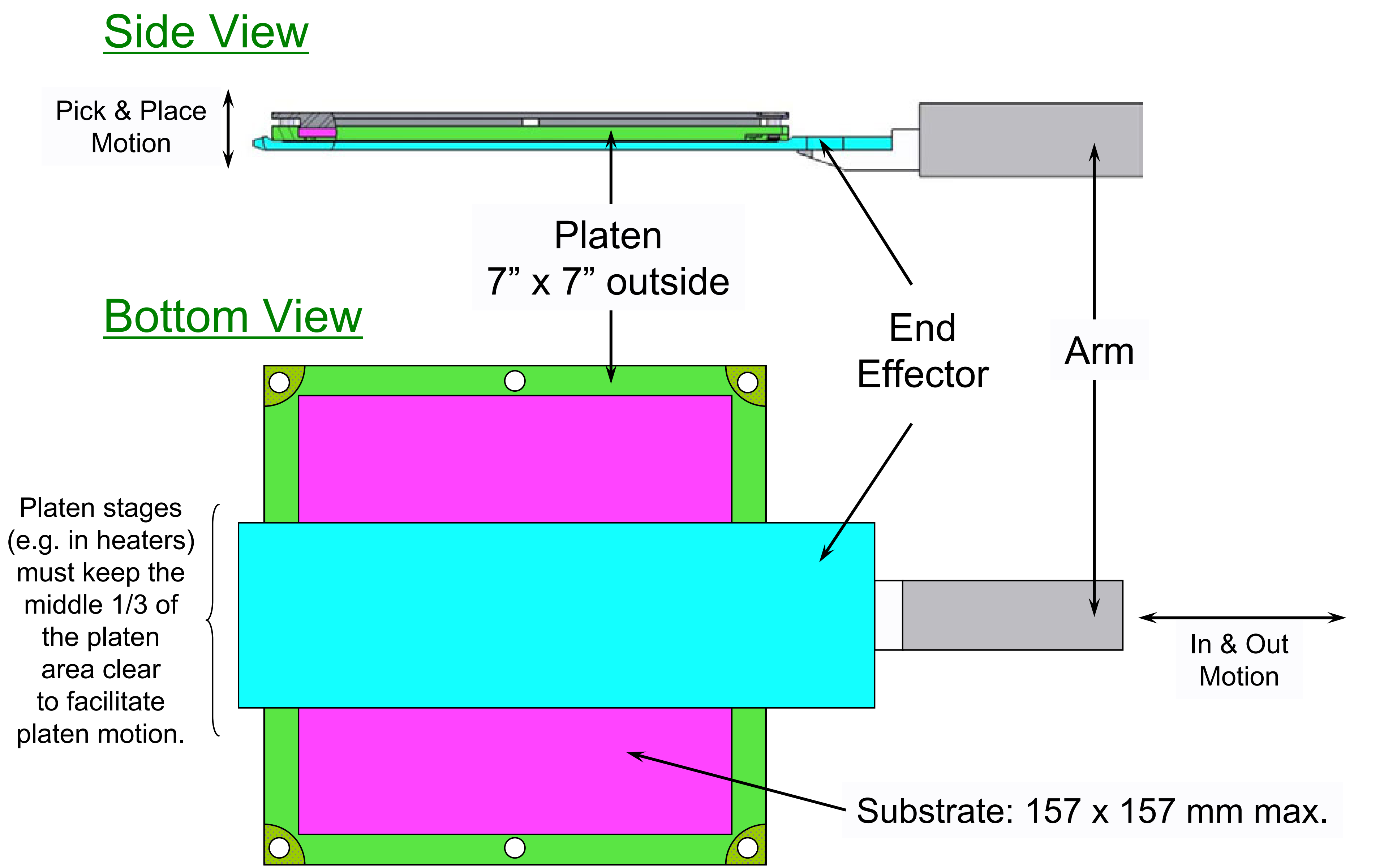
Substrates go in a Platen



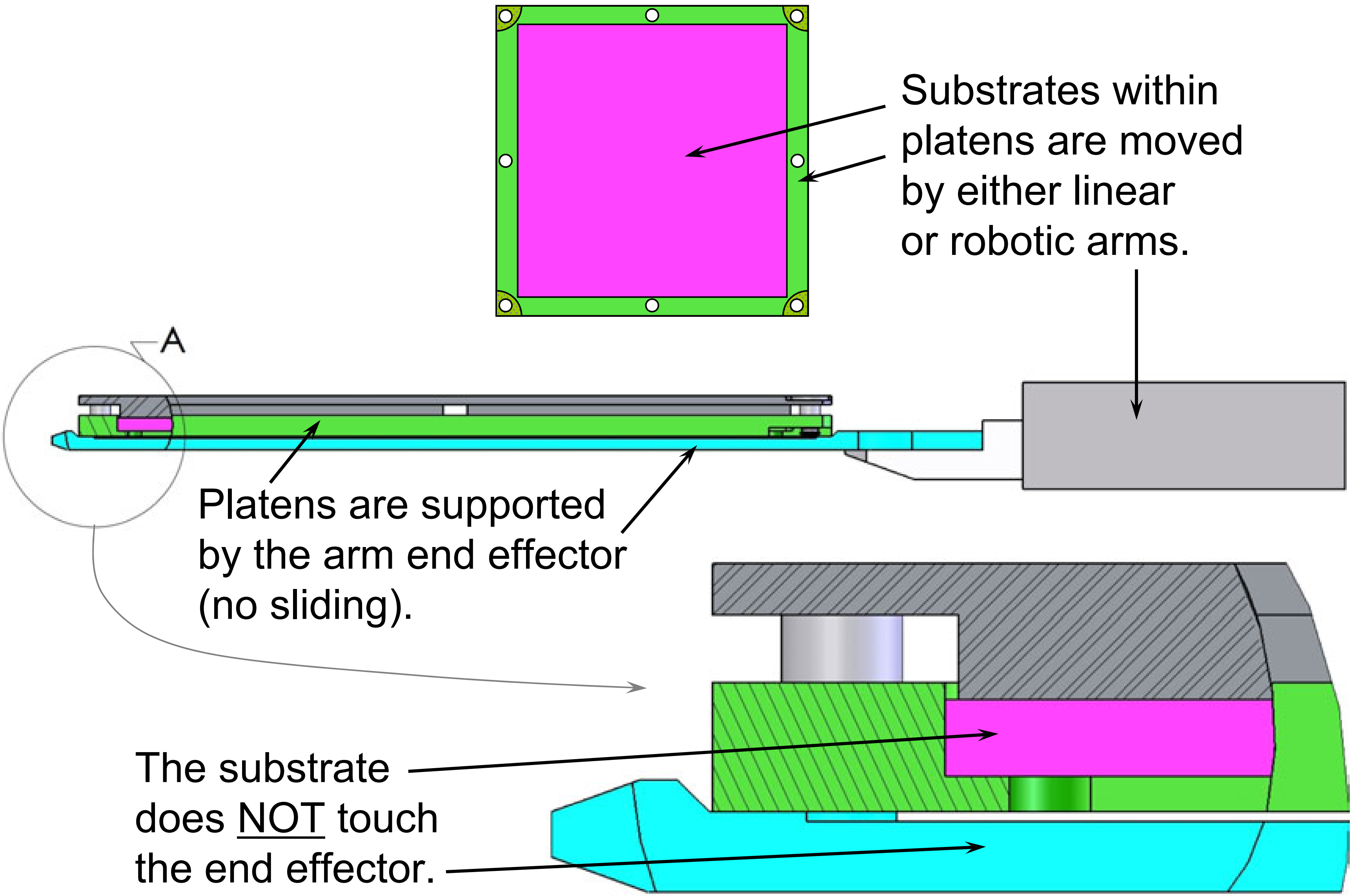
Examples of multiple, smaller, substrates using the standard platen size.



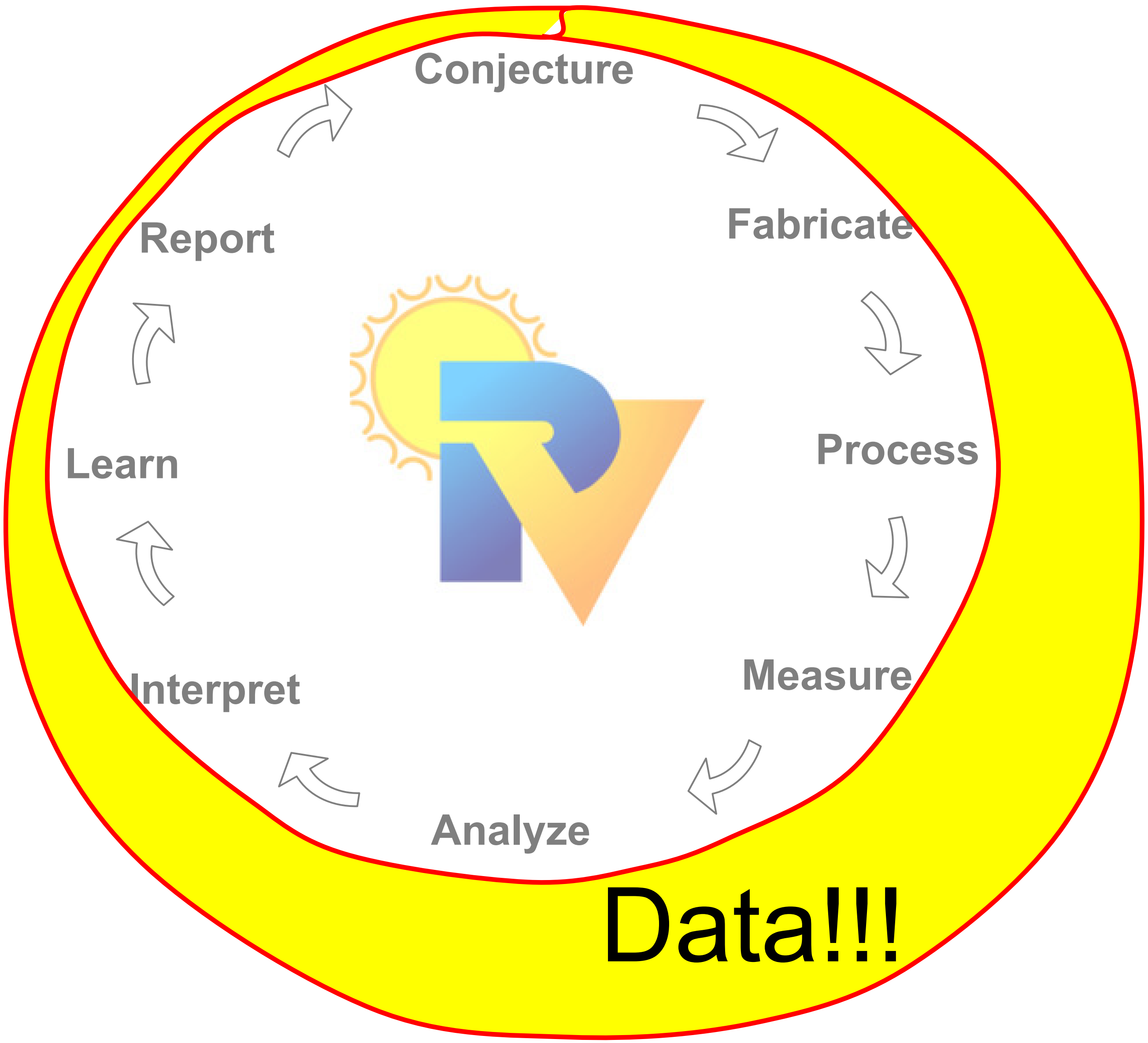
Platen Manipulation



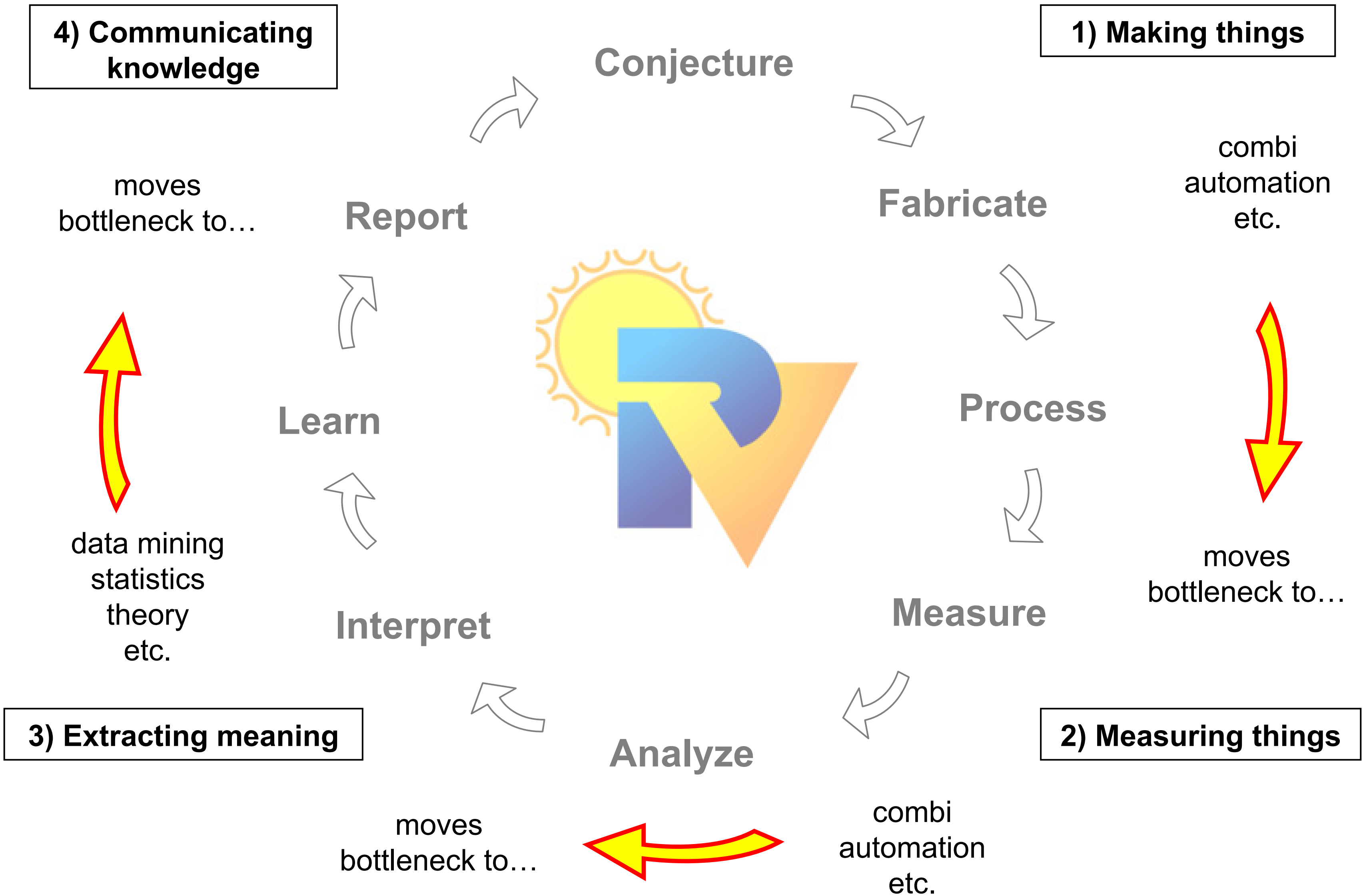
“Pick & Place” Intra-Tool Motion



One constant…



Note: Combi moves the bottlenecks



The S&TF First Floor